Formation of ultra-compact X-ray binaries through circum-binary disk-driven mass transfer

Bo Ma and Xiang-Dong Li

Department of Astronomy, Nanjing University, Nanjing 210093, China; xiaomabo@gmail.com, lixd@nju.edu.cn

ABSTRACT

The formation of ultra-compact X-ray binaries (UCXBs) has not been well understood. Previous works show that ultra-short orbital periods (< 1 hr) may be reached through mass transfer driven by magnetic braking in normal low/intermediate-mass X-ray binaries (L/IMXBs) only for an extremely small range of initial binary parameters, which makes it difficult to account for the rather large population of UCXBs. In this paper we report the calculated results on mass transfer processes in L/IMXBs with a circum-binary disk. We show that when the orbital angular momentum loss due to a circum-binary disk is included, ultra-short orbital periods could be reached for a relatively wide range of initial binary parameters. The results of our binary models suggest an alternative formation channel for UCXBs.

Subject headings: binaries: close – stars:evolution – X-rays: binaries

1. Introduction

Ultra-compact X-ray binaries (UCXBs) are X-ray sources with very short orbital periods ($P < 1$ hr). They are thought to be powered by accretion from a Roche-lobe (RL) filling donor star to a neutron star (NS). The donor has to be compact, such as the helium (or more heavier elements) core of an evolved giant star or a white dwarf (WD), to fit in the small RL (Nelson et al. 1986). Spectra observations have shown possible C/O or He/N features in some of the UCXBs or UCXB candidates (Nelemans et al. 2004, 2006, and references therein). Particular interests have been paid to UCXBs in recent years since they are thought to be potential sources for the gravitational-wave detector *LISA* (Nelemans 2009).

Scenarios for the formation of the UCXBs can be summarized as follows. For UCXBs in globular clusters, they often invoke dynamical processes, such as (1) direct collisions between a NS and a giant (Verbunt 1987; Davies et al. 1992; Rasio & Shapiro 1991; Ivanova et al.

2005; Lombardi et al. 2006), (2) tidal capture of a low-mass main-sequence (MS) star by a NS (Bailyn & Grindlay 1987), and (3) exchange interaction between a NS and a primordial binary (Davies & Hansen 1998; Rasio et al. 2000). All these dynamical scenarios are involved with the so-called common-envelop (CE) phase when the mass transfer between a NS and a (sub)giant is dynamically unstable, which may help form a tight NS+WD or NS+He star binary. After that, the orbital period decays to ultra-short regime through gravitational radiation (GR) until the WD/He star overflows its RL. For UCXBs in the Galactic field where dynamical collisions are not important, generally two CE phases are required to form a tight NS+WD or NS+He star binary, which decays to the ultra-short regime through GR (Tutukov& Yungelson 1993; Iben et al. 1995; Yungelson et al. 2002; Belczynski & Taam 2004). An alternative formation channel of UCXBs is through stable mass transfer in normal low/intermediate-mass X-ray binaries (L/IMXBs) driven by magnetic braking (MB; Verbunt & Zwaan 1981), which is now called the "magnetic capture" scenario (Paczynski & Sienkiewicz 1981; Pylyser & Savonije 1988; Podsiadlowski et al. 2002; Nelson & Rappaport 2003; van der Sluys et al. 2005a). However, van der Sluys et al. (2005a) found that only a very small range of initial parameters are allowed for the binaries to evolve to UCXBs through this channel within the Hubble time. This makes it impossible to account for the relatively large number of observed UCXBs. Another problem of this scenario is related to the efficiency of MB. Observations of some rapid rotators in young, open clusters seem to be contradicted with the MB law originally suggested by Verbunt & Zwaan (1981), and a modified magnetic braking law was proposed to resolve this problem (Queloz et al. 1998; Sills et al. 2000). van der Sluys et al. (2005b) showed that, if this new magnetic braking law is adopted, no UCXBs can be formed through the magnetic capture channel.

In this paper we propose an alternative scenario for the formation of UCXBs through mass transfer between a NS and a MS star. We assume that during Roche-lobe overflow (RLOF), a small fraction of the mass lost from the donor forms a circum-binary (CB) disk around the binary rather accretes onto the NS (van den Heuvel 1994). Previous works have shown that a CB disk can extract orbital angular momentum from the binary effectively (Spruit & Taam 2001; Taam & Spruit 2001), and enhance the mass transfer rate, thus considerably influence the binary evolution (Chen & Li 2006; Chen et al. 2006). In this work we explore the possible role of CB disks in the formation of UCXBs. In §2 we introduce the binary evolution code and the input physics incorporated in our calculations. In §3 we present the calculated results and compare them with observations. The implications of our model and related uncertainties are discussed in §4.

2. Evolutionary code and Input physics

2.1. The stellar evolution code

We use the STAR programme, originally developed by Eggleton (1971, 1972) and updated by other authors (Han et al. 1994; Pols et al. 1995), to compute the binary evolution. The ratio of mixing length to pressure scale height $\chi = l/H_p$ is set to be 2.0 and convective overshooting parameter to be $os = 0.12$, implying a $0.24H_p$ overshooting distance. The opacity table is taken from Hubbard & Lampe (1969), Rogers & Iglesias (1992) and Alexander & Ferguson (1994). Solar compositions ($X = 0.70$, $Y = 0.28$ and $Z = 0.02$) are adopted. The binary system is initially composed of a NS primary of mass M_1 and a zero-age main-sequence (ZAMS) secondary of mass M_2 with an orbital period $P_{\rm i}$. The effective radius of the RL for the secondary star is calculated from Eggleton (1983) equation,

$$R_{\rm L,2} = \frac{0.49q^{-2/3}a}{0.6q^{-2/3} + \ln(1 + q^{-1/3})}, \tag{1}$$

where $q = M_2/M_1$ is the mass ratio of the binary components, and a is the orbital separation. The rate of mass transfer via RLOF is calculated with $-\dot{M}_2 = RMT \cdot \max[0, (R_2/R_{\rm L,2} - 1)^3]M_\odot{\rm yr}^{-1}$ in the code, where R_2 is the radius of the secondary, and we set $RMT = 10^3$.

2.2. Angular momentum loss mechanisms

We assume that the secondary star rotates synchronously with the binary orbital revolution, since the timescale of tidal synchronization is generally much shorter than the characteristic evolutionary timescale of the binaries considered here. We take into account four kinds of angular momentum loss mechanisms described as follows.

(1) Gravitational radiation, which becomes important when the orbital period is short. The angular momentum loss rate is given by (Landau & Lifshitz 1975)

$$\frac{{\rm d}J}{{\rm d}t}|_{\rm GR} = -\frac{32}{5}\frac{G^{7/2}}{c^5}\frac{M_1^2M_2^2(M_1 + M_2)^{1/2}}{a^{7/2}}, \tag{2}$$

where J, G and c are the orbital angular momentum, gravitational constant and speed of light, respectively.

(2) CB disk. We assume that a small fraction $\delta(\ll 1)$ of the mass lost from the donor feeds into the CB disk rather leaves the binary, which yields a mass injection rate of the CB disk as $\dot{M}_{\rm CB} = -\delta\dot{M}_2$. Tidal torques are then exerted on the binary by the CB disk via gravitational

interaction, thus extracting the angular momentum from the binary system. The angular momentum loss rate via the CB disk is estimated to be (Spruit & Taam 2001)

$$\frac{\mathrm{d}J}{\mathrm{d}t}|_{\mathrm{CB}} = -\gamma\left(\frac{2\pi a^2}{P}\right)\dot{M}_{\mathrm{CB}}\left(\frac{t}{t_{\mathrm{vi}}}\right)^{1/3}, \tag{3}$$

where $\gamma^2 = r_{\mathrm{i}}/a = 1.7$ (r_{i} is the inner radius of the CB disk), t is the time since mass transfer begins. In the standard α-viscosity disk (Shakura & Sunyaev 1973), the viscous timescale t_{vi} at the inner edge r_{i} of the CB disk is given by $t_{\mathrm{vi}} = 2\gamma^3 P/3\pi\alpha\beta^2$, where α is the viscosity parameter (we set $\alpha = 0.01$ in the following calculations), $\beta = H_{\mathrm{i}}/r_{\mathrm{i}} \sim 0.03$ (Belle et al. 2004), and H_{i} is the scale height of the disk. When $\dot{M}_{\mathrm{CB}}$ is sufficiently large, the mass transfer will become dynamically unstable, so we add an ad hoc term

$$\exp(1 + \dot{M}_2/2\dot{M}_{\mathrm{Edd}}) \text{ if } -\dot{M}_2 > 2\dot{M}_{\mathrm{Edd}}$$

to Eq. (3) to suppress the CB disk-induced angular momentum loss rate when the mass loss rate is high. We find that this term does not influence the evolutionary tracks considerably, only expanding the parameter space of δ suitable for UCXB formation within the Hubble time by $\sim 10\% - 20\%$. Here the Eddington accretion limit is expressed as

$$\dot{M}_{\mathrm{Edd}} = 3.6\times10^{-8}\left(\frac{M_1}{1.4M_\odot}\right)\left(\frac{0.1}{\eta}\right)\left(\frac{1.7}{1+X}\right)M_\odot\mathrm{yr}^{-1}, \tag{4}$$

where $\eta = GM_1/Rc^2$ is the energy release efficiency through accretion (R the NS radius), and X is the mass fraction of hydrogen in the accreting material.

(3) Mass loss. Similar as in Podsiadlowski et al. (2002), we assume that the NS accretion rate is limited to the Eddington accretion rate, and that when the mass transfer rate is less than $\dot{M}_{\mathrm{Edd}}$, half of the mass is accreted by the NS, i.e., $\dot{M}_1 = \min(\dot{M}_{\mathrm{Edd}}, -\dot{M}_2/2)$. The excess mass is lost in the vicinity of the NS through isotropic winds, carrying away the specific angular momentum of the NS, i.e.

$$\frac{\mathrm{d}J}{\mathrm{d}t}|_{\mathrm{ML}} \simeq \begin{cases} \frac{1}{2}\dot{M}_2 a_1^2\omega, & |\dot{M}_2| < 2\dot{M}_{\mathrm{Edd}} \\ (\dot{M}_2 + \dot{M}_{\mathrm{Edd}})a_1^2\omega, & |\dot{M}_2| \geq 2\dot{M}_{\mathrm{Edd}} \end{cases} \tag{5}$$

where $a_1 = aM_2/(M_1 + M_2)$ is the orbital radius of the NS, and ω is the orbital angular velocity of the binary.

(4) Magnetic braking. We use the saturated magnetic braking law suggested in Sills et al. (2000),

$$\frac{\mathrm{d}J}{\mathrm{d}t}|_{\mathrm{MB}} = \begin{cases} -K\omega^3\left(\frac{R_2}{R_\odot}\right)^{1/2}\left(\frac{M_2}{M_\odot}\right)^{-1/2}, & \omega \leq \omega_{\mathrm{cr}} \\ -K\omega_{\mathrm{cr}}^2\omega\left(\frac{R_2}{R_\odot}\right)^{1/2}\left(\frac{M_2}{M_\odot}\right)^{-1/2}, & \omega > \omega_{\mathrm{cr}} \end{cases} \tag{6}$$

where $K = 2.7 \times 10^{47}$ gcm^{2}s (Andronov et al. 2003), $\omega_{\rm cr}$ is the critical angular velocity at which the angular momentum loss rate reaches a saturated state, and can be estimated as (Krishnamurthi et al. 1997),

$$\omega_{\rm cr}(t) = \omega_{\rm cr,\odot} \frac{\tau_{\rm t_0,\odot}}{\tau_{\rm t}}, \tag{7}$$

where $\omega_{\rm cr,\odot} = 2.9 \times 10^{-5}$ Hz, $\tau_{\rm t_0,\odot}$ is the global turnover timescale for the convective envelope of the Sun at its current age, $\tau_{\rm t}$ for the secondary at age t, solved by integrating the inverse local convective velocity over the entire surface convective envelope (Kim & Demarque 1996). Following Podsiadlowski et al. (2002), an ad hoc factor is also added to Eq. (6)

$$\exp(-0.02/q_{\rm con} + 1) \text{ if } q_{\rm con} < 0.02,$$

where $q_{\rm con}$ is the mass fraction of the surface convective envelope. This term is used to reduce the strength of MB when the star has a very small convective envelope and hence does not have a strong magnetic field.

3. Results

3.1. Parameter space of P_i and $M_{2,\rm i}$

Similar as in van der Sluys et al. (2005a), we define UCXBs as X-ray binaries with $P < 50$ min. The binary systems we considered are initially composed of a 1.4 $M_\odot$ NS and a $0.5-5M_\odot$ ZAMS star. We have performed calculations of a large number of binary evolutions, to search suitable values in the three dimensional binary parameter space δ (assumed to be constant through one evolutionary sequence), $P_{\rm i}$ and $M_{2,\rm i}$ for binaries evolved to UCXBs within the age of the universe (13.7 Gyr). The distribution of $P_{\rm i}$ and $M_{2,\rm i}$ for successful systems is shown in Fig. 1 with $P_{\rm i} \sim 0.7-1$ d and $M_{2,\rm i} \sim 1-3.5\,M_\odot$. When the donor mass $M_{2,\rm i} > 3.5M_\odot$, the mass transfer becomes dynamically unstable (see also Podsiadlowski et al. 2002). Comparing with the results of van der Sluys et al. (2005b) one can find that there is a relatively large parameter space for the formation of UCXBs if there is a CB disk at work.

3.2. Limits and influence of δ

The possible distribution of δ and $P_{\rm i}$ with $M_{2,\rm i} = 1.1M_\odot$ is shown in Fig. 2. To illustrate the effects of δ on the binary evolution, in Figs. 3−5, we plot the exemplarily evolutionary tracks of the secondary in the H-R diagram, the evolution of the donor mass and period as a function of age respectively, for a binary system with $M_{2,\rm i} = 1.1M_\odot$, $P_{\rm i} = 1.04$ d and different

values of δ. The lower limit of δ is determined by the constraint that age of the binary should be less than 13.7 Gyr: a larger value of δ leads to shorter formation time, as seen from Fig. 5; if δ is too small, the binary will not be able to reach the 50 min period within 13.7 Gyr due to inefficient angular momentum loss. The upper limit of δ is determined by two conditions. The first is that the minimum orbital period $P_{\rm min}$ should be less than 50 min. With larger values of δ, the donor will spend relatively less time on the MS, leaving a smaller degenerate helium core. According to the mass-radius relation of degenerate stars, the smaller mass, the larger radius, which corresponds to a larger $P_{\rm min}$. The second is $\delta < 0.015$, because we find that mass transfer becomes unstable in most cases if $\delta > 0.015$.

The formation and evolutionary paths of UCXBs depend on the adopted values of δ. In the case of $M_{\rm 2,i} = 1.1 M_{\odot}$ and $P_{\rm i} = 1.04$ d, for example, when $\delta < 0.0055$, the orbital period first decreases with mass transfer until the donor star loses its outer envelope and shrinks rapidly at $P \sim 0.1 - 0.2$ d. This causes a cessation of mass transfer. In the subsequent evolution the orbital period may decrease down to the ultra-short regime under the effect of GR, until the secondary star fills its RL again, and the binary appears as a UCXB. When $\delta \geq 0.0055$ the binary evolves directly into the ultra-short regime with decreasing orbital period.

We need to mention that the distribution of δ depends on the value of the viscous parameter α, which we chose to be 0.01 in our calculations as adopted in Spruit & Taam (2001) and Taam & Spruit (2001). This is about an order of magnitude lower than the value ($\sim 0.1 - 0.4$) inferred by King et al. (2007) for fully ionized, thin accretion disks from observations of dwarf nova outbursts and outbursts of X-ray transients. However, the α value estimated by King et al. (2007) is an average one over the entire disk, while here it is at the inner edge of the disk (Spruit & Taam 2001), which may be smaller due to the boundary condition (e.g. Papaloizou & Nelson 2003; Winters et al. 2003; Fromang & Nelson 2006). Additionally, since the CB disk is located outside the binary, and hence shielded from X-ray irradiation from the NS by the accretion disk around the NS and the secondary, the α value in a CB disk might also be smaller than in accretion disks. Taking account of the above facts, we suggest to regard Fig. 2 as an optimistic case for the distribution of δ. Nevertheless, from Eqs. (3) one can see that the CB disk-induced angular momentum loss rate is proportional to $\alpha^{1/3}\delta$. So if keeping $\alpha^{1/3}\delta$ constant, the binary evolution will be exactly the same (this has been verified by our test calculations), implying a predictable δ distribution for a given value of α.

3.3. Comparison with observations

There are currently 10 UCXBs with known periods, 5 of which are persistent sources and 5 are transients. We list the orbital periods $P_{\rm orb}$ and mean mass accreting rates $\dot{M}_1$ (or the upper limit of $\dot{M}_1$) of these UCXBs in Table 1. The $\dot{M}_1$s listed in this table for persistent UCXBs are calculated by using the luminosities mentioned in the references and assuming accretion onto a $1.4M_\odot$ NS with a 10 km radius, while those for transient sources are from the estimates of Krauss et al. (2007), Watts et al. (2008) and Lasota et al. (2008). To compare observations with our CB disk-assisted binary model, we plot the $\dot{M}_1(= -\dot{M}_2/2)$ vs. $P_{\rm orb}$ relations in Fig. 6 for binary systems with $M_2 = 1.1M_\odot$, $P_{\rm i} = 1.04$ d and $\delta = 0.005 - 0.009$, and in Fig. 7 for binary systems with $M_2 = 1.1M_\odot$, $\delta = 0.005$ and $P_{\rm i} = 0.94 - 1.04$ d. Note that in these two figures the values of $\dot{M}_1$ are not assumed to be limited to $\dot{M}_{\rm Edd}$, so that possible super-Eddington accretion can be allowed. In this way we can compare our results with observations directly. We also indicate in Figs. 6 and 7 whether the accretion disks in the LMXBs are thermally and viscously stable, according to the stability criterion for a mixed-composition ($X = 0.1$, $Y = 0.9$) disk from Lasota et al. (2008) [1]. We use the symbols $\times$, $*$, and $+$ on the evolutionary tracks to denote where the hydrogen composition X of the donor becomes 0.3, 0.2, and 0.1, respectively, to show that the criterion of Lasota et al. (2008) is applicable here. The positions of UCXBs are marked in these two figures with circles and triangles for persistent and transient sources, respectively. Besides them, we also include 18 NS LMXBs with known P and $\dot{M}_1$ (data are taken from Liu et al. 2007; Watts et al. 2008; Heinke et al. 2009).

A comparison between our CB disk-assisted binary models and the observations of (compact) NS LMXBs suggesting that it is possible to form UCXBs from normal LMXBs. We note that three of the UCXBs are in globular clusters, indicating low metallicities in these systems. However, from our calculations we find that change of metallicities does not significantly affect the binary evolution when the CB disk is involved. The 11-min UCXB 4U 1820−30 is particularly interesting because of its negative period derivative $\dot{P}/P = -3.5 \pm 1.5 \times 10^{-8}$

[1]We notice two points about the persistent/transient criterion in UCXBs. Firstly, in Lasota et al. (2008) it is found that three of the five persistent UCXBs should be transient if their accretion disks are composed of pure helium or elements heavier than helium (C/O). However, in our CB disk model, the disks are not composed of pure helium but of mixed-compositions, so the accretion disks in these UCXBs are thermally stable, consistent with observations. Secondly, the transient source 4U1626−67 should be persistent according to the criterion, but it is transient in a different way: its outbursts do not last tens of days but tens of years (Krauss et al. 2007). The value of $\dot{M}_1$ in Table 1 is calculated from Eqs. (4) in Krauss et al. (2007) assuming a distance of 3 kpc (Chakrabarty 1998) and the time between outbursts to be 30 years. If the recurrence time is as long as 1000 yrs, it will yield a much lower $\dot{M}_1$ (Lasota et al. 2008), and may help to resolve this transient/persistent problem.

yr^{-1} (van der Klis et al. 1993a; Chou & Grindlay 2001), which is inconsistent with the lower limit ($\dot{P}/P > 8.8 \times 10^{-8}\ \mathrm{yr}^{-1}$) of the standard evolutionary scenario (Rappaport et al. 1997). While previous explanations for this negative period derivative invoke acceleration of the binary by a distant third companion in a hierarchical triple system, or by the cluster potential (Tan et al. 1991; van der Klis et al. 1993b; King et al. 1993; Chou & Grindlay 2001), our CB disk scenario may present an alternative interpretation of this negative period derivative (see Fig. 5).

4. Discussion and Conclusion

During RLOF mass transfer, a CB disk may be formed as a result of mass outflow from the accretion disk, and has been invoked as an efficient process for the removal of orbital angular momentum (Taam & Spruit 2001). We propose a scenario for the formation of UCXBs from L/IMXBs with the aid of a CB disk in this work. The suitable binary parameter space ($M_{2,\mathrm{i}}$ and P_{i}) with reasonable choice of the CB disk parameter δ for the formation of UCXBs within 13.7 Gyr is found to be significantly larger than in previous "magnetic capture" model (van der Sluys et al. 2005a,b). This difference is caused by the fact that the bifurcation period is considerably increased if the CB disk is included. In L/IMXB evolution the bifurcation period P_{bif} is defined as the initial orbital period when the donor star is on ZAMS, which separates the formation of converging systems from diverging systems. Because the value of P_{bif} depends strongly on the angular momentum loss mechanisms (van der Sluys et al. 2005a; Ma & Li 2008), we would expect P_{bif} to be significantly changed when the CB disk is included in the binary model. In Table 2 we present the calculated values of P_{bif} for binary systems consisting of a $1.4\,M_{\odot}$ NS and a $1.1 M_{\odot}$ secondary, with ($\delta = 0.002 - 0.01$) and without a CB disk. We also list the corresponding values of the period (P_{rlof}) at which RLOF begins (Podsiadlowski et al. 2002; Ma & Li 2008). According to the investigation of Podsiadlowski et al. (2002) and van der Sluys et al. (2005a), binary systems with initial orbital period slightly below the bifurcation period can achieve the shortest possible orbital period. We list the shortest periods for binary systems with certain value of δ within 13.7 Gyr in Table 2, which clearly indicate that, (1) the larger δ, the larger P_{bif} and P_{rlof}, and (2) UCXBs ($P < 50$ min) are not likely to form in such a scenario without the aid of CB disks ($\delta = 0$).

We note here that when the binaries reach their minimum periods where the donors become degenerate, their orbital periods will bounce back into the period-increasing phase. Our code cannot follow the binary evolution with a degenerate donor star. It is likely that the observed UCXBs may be explained as binaries both evolving to shorter orbital peri-

ods with a hydrogen-deficient, non-degenerate donor star (as presented in Figs. 6 and 7), and with a degenerate WD donor during a period-increasing phase (Yungelson et al. 2002; Nelson & Rappaport 2003; Deloye & Bildsten 2003; Deloye et al. 2007). In addition, the helium-donor channel (or semi-degenerate channel) may also contribute to the formation of UCXBs (Savonije et al. 1986). Currently it is difficult to compare the (spectral) theoretical models for hydrogen-deficient accretion disks with observations, or directly measure the orbital period derivative, one possible criterion to discriminate UCXBs in the period-decreasing/increasing phases is related to the donor masses, which, together with the orbital periods, allow to determine the mass-radius relation of the donor. Our calculations show that the UCXB's donor mass is around $\sim 0.1M_{\odot}$ in the period-decreasing phase at $P \sim 40$ mins, while in the period increasing phase, the donor mass should be around $0.01M_{\odot}$ (e.g. Yungelson et al. 2002; Nelson & Rappaport 2003). Previously investigations on the UCXBs XTE J1807−294 (Falanga et al. 2005), SWIFT J1756.9−2508 (Krimm et al. 2007), and XTE J0929−314 (Galloway et al. 2002) have shown that the donors should be WDs unless the binary orbital inclination is very small ($< 10°$), because of their small mass functions, while XTE 1751−305 is more likely to be in the period-decreasing phase due to its relatively larger mass function (Markwardt et al. 2002). Observationally there seem to be more systems in the period-increasing phase than in the period-decreasing phase. This may be addressed by the fact that UCXBs spend longer mass-transfer time in the former ($> 10^8$ yr, see Rasio et al. 2000; Deloye & Bildsten 2003) than in the latter phase ($\sim 10^7$ yr, see Nelson & Rappaport 2003, and this wrok). From Table 1 there appears to be an apparent accumulation of systems with $P \sim 40 - 50$ mins. The reason may lie in that (1) during the period-increasing phase, UCXBs spend more time at larger orbital periods (see Deloye & Bildsten 2003, Fig. 9), and (2) when $P > 50$ mins, most of these systems become transient sources with very weak accretion ($< 10^{-12}M_{\odot}\mathrm{yr}^{-1}$). From the calculation of Deloye et al. (2005), these semi-degenerate systems should mainly distribute at 40 mins $< P <$ 90 mins (see Deloye et al. 2005, Fig. 5). Most of them should be transients (see Deloye et al. 2005, Fig. 2), among which the longer the orbital period, the weaker the accretion will be, thus the more difficult to be detected. These together account for the accumulation of UCXBs with $P \sim 40 - 50$ mins. Obviously a thorough population synthesis is needed to address the contribution to UCXBs from systems with non-degenerate, semi-degenerate and degenerate donors.

However, there exist some issues in the CB disk scenario, especially the existence of CB disk in LMXBs. Dubus et al. (2002) suggest that CB disks are prospective to be observed in infrared and sub-millimeter band. Although observations have shown evidence for the existence of CB disks in young binary systems (Monnier et al. 2008; Ireland & Kraus 2008), magnetic cataclysmic variables (Howell et al. 2006; Brinkworth et al. 2007; Dubus et al. 2007; Hoard et al. 2007), and black hole LMXBs (Muno & Mauerhan 2006; Gallo et al. 2007),

more infrared observations are still needed to confirm or disprove the hypothesis that CB disk may exist in some LMXBs (e.g. Dubus et al. 2004). Additionally, the CB disk parameter δ is poorly known, and it is possible to change with time or mass transfer rate. The strong dependence of LMXB evolution on the value of δ prevents accurate estimation of the contribution of such binaries to UCXBs. More generally, we do not insist that there should be a CB disk in L/IMXBs, but argue that a mechanism that mimics its features may be an important ingredient for understanding the overall period distribution of UCXBs as well as cataclysmic variable binaries (Willems et al. 2005).

Recent *Chandra* observations of nearby elliptical galaxies have revealed a population of luminous point X-ray sources, which are likely to be LMXBs with accretion rates $\dot{M} > 10^{-8}M_{\odot}\ \mathrm{yr}^{-1}$ (e.g. Gilfanov 2004; Kim & Fabbiano 2004). These sources are explained either as transient LMXBs in which NSs accreting from a red-giant star in wide orbits ($P > 10$ d) (Piro & Bildsten 2002) or ultra-compact binaries ($P \sim 8-10$ min) with a $0.06-0.08M_{\odot}$ He or C/O donor (Bildsten & Deloye 2004). Our calculations suggest that normal LMXBs with a CB disk may present a plausible alternative interpretation for these luminous X-ray sources. We show in Fig. 8 the mean lifetime spent by LMXBs evolved to UCXBs at certain luminosity with $\delta = 0.005$. Here by the luminosity we mean the "potential maximum luminosity", where the Eddington limit is removed and nearly all the mass lost by the donor is assumed to be accreted by the NS. From this figure we see that the UCXBs can be luminous ($L > 10^{38}$ ergs^{-1}) for $\sim 10^7$ yr, and the X-ray lifetime decreases sharply when $L > 3-5\times10^{38}$ ergs^{-1}, which may account for the break in the luminosity function at $\sim 5\times10^{38}$ ergs^{-1} (Kim & Fabbiano 2004). A distinct feature of this explanation is that the luminous X-ray sources are predicted to be short-period, persistent rather transient sources.

We thank an anonymous referee for his/her valuable comments that helped improve the original manuscript. BM thanks W.-C. Chen and P. P. Eggleton for helpful discussions and suggestions. This work was supported by Natural Science Foundation of China under grant 10873008 and National Basic Research Program of China (973 Program 2009CB824800).

REFERENCES

Alexander, D. R., & Ferguson, J. W. 1994, ApJ, 437, 879

Andronov, N., Pinsonneault, M., & Sills, A. 2003, ApJ, 582, 358

Bailyn, C. D., & Grindlay, J. E. 1987, ApJ, 316, L25

Bailyn, C. D. 1995, ARA&A, 33, 133

Begelman, M. C. 2002, ApJ, 568, L97

Belczynski, K., & Taam, R. E. 2004, ApJ, 603, 690

Belle, K. E., Sanghi, N., Howell, S. B., Holberg, J. B., & Williams, P. T. 2004, AJ, 128, 448

Bildsten, L., & Deloye, C. J. 2004, ApJ, 607, L119

Brinkworth, C. S., et al. 2007, ApJ, 659, 1541

Ma, Bo, & Li, X. D. 2008, arXiv:0810.2009

Chakrabarty, D. 1998, ApJ, 492, 342

Chen, W.-C., & Li, X.-D. 2006, MNRAS, 373, 305

Chen, W.-C., Li, X.-D., & Qian, S.-B. 2006, ApJ, 649, 973

Chen, W.-C., & Li, X.-D. 2007, ApJ, 658, L51

Chou, Y., & Grindlay, J. E. 2001, ApJ, 563, 934

Davies, M. B., Benz, W., & Hills, J. G. 1992, ApJ, 401, 246

Davies, M. B., & Hansen, B. M. S. 1998, MNRAS, 301, 15

Deloye, C. J., & Bildsten, L. 2003, ApJ, 598, 1217

Deloye, C. J., Bildsten, L., & Nelemans, G. 2005, ApJ, 624, 934

Deloye, C. J., Taam, R. E., Winisdoerffer, C., & Chabrier, G. 2007, MNRAS, 381, 525

Dieball, A., Knigge, C., Zurek, D. R., Shara, M. M., Long, K. S., Charles, P. A., Hannikainen, D. C., & van Zyl, L. 2005, ApJ, 634, L105

Dubus, G., Lasota, J.-P., Hameury, J.-M., & Charles, P. 1999, MNRAS, 303, 139

Dubus, G., Taam, R. E., & Spruit, H. C. 2002,ApJ, 569, 395

Dubus, G., Campbell, R., Kern, B., Taam, R. E., & Spruit, H. C. 2004, MNRAS, 349, 869

Dubus, G., Taam, R. E., Hull, C., Watson, D. M., & Mauerhan, J. C. 2007, ApJ, 663, 516

Eggleton, P. P. 1971, MNRAS, 151, 351

Eggleton, P. P. 1972, MNRAS, 156, 361

Eggleton, P. P. 1983, ApJ, 268, 368

Falanga, M., et al. 2005, A&A, 436, 647

Fromang, S., & Nelson, R. P. 2006, A&A, 457, 343

Gallo, E., Migliari, S., Markoff, S., Tomsick, J. A., Bailyn, C. D., Berta, S., Fender, R., & Miller-Jones, J. C. A. 2007, ApJ, 670, 600

Galloway, D. K., Chakrabarty, D., Morgan, E. H., & Remillard, R. A. 2002, ApJ, 576, L137

Gilfanov, M. 2004, MNRAS, 349, 146

Han, Z., Podsiadlowski, P., & Eggleton, P. P. 1994, MNRAS, 270, 121

Hannikainen, D. C., Charles, P. A., van Zyl, L., Kong, A. K. H., Homer, L., Hakala, P., Naylor, T., & Davies, M. B. 2005, MNRAS, 357, 325

Harris, W. E. 1996, AJ, 112, 1487

Heinke, C. O., Jonker, P. G., Wijnands, R., & Taam, R. E. 2007, ApJ, 660, 1424

Heinke, C. O., Jonker, P. G., Wijnands, R., Deloye, C. J., & Taam, R. E. 2009, ApJ, 691, 1035

Hubbard, W. B., & Lampe, M. 1969, ApJS, 18, 297

Hoard, D. W., Howell, S. B., Brinkworth, C. S., Ciardi, D. R., & Wachter, S. 2007, ApJ, 671, 734

Howell, S. B., et al. 2006, ApJ, 646, L65

Iben, I. J., Tutukov, A. V., & Yungelson, L. R. 1995, ApJS, 100, 233

Ivanova, N., Rasio, F. A., Lombardi, J. C., Jr., Dooley, K. L., & Proulx, Z. F. 2005, ApJ, 621, L109

Ireland, M. J., & Kraus, A. L. 2008, ApJ, 678, L59

Juett, A. M., & Chakrabarty, D. 2006, ApJ, 646, 493

Kim, D.-W., & Fabbiano, G. 2004, ApJ, 611, 846

Kim, Y.-C., & Demarque, P. 1996, ApJ, 457, 340

King, I. R., et al. 1993, ApJ, 413, L117

King, A. R., Kolb, U., & Szuszkiewicz, E. 1997, ApJ, 488, 89

King, A. R., Pringle, J. E., & Livio, M. 2007, MNRAS, 376, 1740

Krauss, M. I., Schulz, N. S., Chakrabarty, D., Juett, A. M., & Cottam, J. 2007, ApJ, 660, 605

Krimm, H. A., et al. 2007, ApJ, 668, L147

Krishnamurthi, A., Pinsonneault, M. H., Barnes, S., & Sofia, S. 1997, ApJ, 480, 303

Kuulkers, E., den Hartog, P. R., in't Zand, J. J. M., Verbunt, F. W. M., Harris, W. E., & Cocchi, M. 2003, A&A, 399, 663

Landau, L. D., & Lifshitz, E. M. 1975, Course of theoretical physics - Pergamon International Library of Science, Technology, Engineering and Social Studies, Oxford: Pergamon Press, 1975, 4th rev.engl.ed.,

Lasota, J.-P., Dubus, G., & Kruk, K. 2008, A&A, 486, 523

Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2007, A&A, 469, 807

Lombardi, J. C., Jr., Proulx, Z. F., Dooley, K. L., Theriault, E. M., Ivanova, N., & Rasio, F. A. 2006, ApJ, 640, 441

Markwardt, C. B., Swank, J. H., Strohmayer, T. E., in 't Zand, J. J. M., & Marshall, F. E. 2002, ApJ, 575, L21

Monnier, J. D., Tannirkulam, A., Tuthill, P. G., Ireland, M., Cohen, R., Danchi, W. C., & Baron, F. 2008, ApJ, 681, L97

Muno, M. P., & Mauerhan, J. 2006, ApJ, 648, L135

Nelemans, G. 2009, Classical and Quantum Gravity, in press (astro-ph/0901.1778)

Nelemans, G., Jonker, P. G., Marsh, T. R., & van der Klis, M. 2004, MNRAS, 348, L7

Nelemans, G., Jonker, P. G., & Steeghs, D. 2006, MNRAS, 370, 255

Nelson, L. A., & Rappaport, S. 2003, ApJ, 598, 431

Nelson, L. A., Rappaport, S. A., & Joss, P. C. 1986, ApJ, 304, 231

Paczynski, B., & Sienkiewicz, R. 1981, ApJ, 248, L27

Paltrinieri, B., Ferraro, F. R., Paresce, F., & De Marchi, G. 2001, AJ, 121, 3114

Papaloizou, J. C. B., & Nelson, R. P. 2003, MNRAS, 339, 983

Piro, A. L., & Bildsten, L. 2002, ApJ, 571, L103

Podsiadlowski, P., Rappaport, S., & Pfahl, E. D. 2002, ApJ, 565, 1107

Pols, O. R., Tout, C. A., Eggleton, P. P., & Han, Z. 1995, MNRAS, 274, 964

Pylyser, E., & Savonije, G. J. 1988, A&A, 191, 57

Queloz, D., Allain, S., Mermilliod, J.-C., Bouvier, J., & Mayor, M. 1998, A&A, 335, 183

Rappaport, S. et al. 1987, ApJ, 322, 842

Rasio, F. A., & Shapiro, S. L. 1991, ApJ, 377, 559

Rasio, F. A., Pfahl, E. D., & Rappaport, S. 2000, ApJ, 532, L47

Rogers, F. J., & Iglesias, C. A. 1992, ApJS, 79, 507

Ruszkowski, M., & Begelman, M. C. 2003, ApJ, 586, 384

Savonije, G. J., de Kool, M., & van den Heuvel, E. P. J. 1986, A&A, 155, 51

Schultz, J. 2003, A&A, 397, 249

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Shaposhnikov, N., & Titarchuk, L. 2004, ApJ, 606, L57

Sidoli, L., Paizis, A., Bazzano, A., & Mereghetti, S. 2006, A&A, 460, 229

Sills, A., Pinsonneault, M. H., & Terndrup, D. M. 2000, ApJ, 534, 335

Spruit, H. C., & Taam, R. E. 2001, ApJ, 548, 900

Taam, R. E., & Spruit, H. C. 2001, ApJ, 561, 329

Tan, J., et al. 1991, ApJ, 374, 291

Tutukov, A. V., & Yungelson, L. R. 1993, Astron. Rep., 37, 411

van den Heuvel, E. P. J. 1994, Saas-Fee Advanced Course 22: Interacting Binaries, 263

van der Klis, M., Hasinger, G., Verbunt, F., van Paradijs, J., Belloni, T., & Lewin, W. H. G. 1993a, A&A, 279, L21

van der Klis, M., et al. 1993b, MNRAS, 260, 686

van der Sluys, M. V., Verbunt, F., & Pols, O. R. 2005a, A&A, 431, 647

van der Sluys, M. V., Verbunt, F., & Pols, O. R. 2005b, A&A, 440, 973

Verbunt, F., & Zwaan, C. 1981, A&A, 100, L7

Verbunt, F. 1987, ApJ, 312, L23

Wang, Z., & Chakrabarty, D. 2004, ApJ, 616, L139

Watts, A. L., Krishnan, B., Bildsten, L., & Schutz, B. F. 2008, MNRAS, 389, 839

Webbink, R. F. 1985, Interacting Binary Stars, 39

Wijnands, R., Homan, J., Heinke, C. O., Miller, J. M., & Lewin, W. H. G. 2005, ApJ, 619, 492

Willems, B. et al. 2007, ApJ, 653, 1263

Winters, W. F., Balbus, S. A., & Hawley, J. F. 2003, ApJ, 589, 543

Yungelson, L. R., Nelemans, G., & van den Heuvel, E. P. J. 2002, A&A, 388, 546

Zdziarski, A. A., Gierliński, M., Wen, L., & Kostrzewa, Z. 2007, MNRAS, 377, 1017

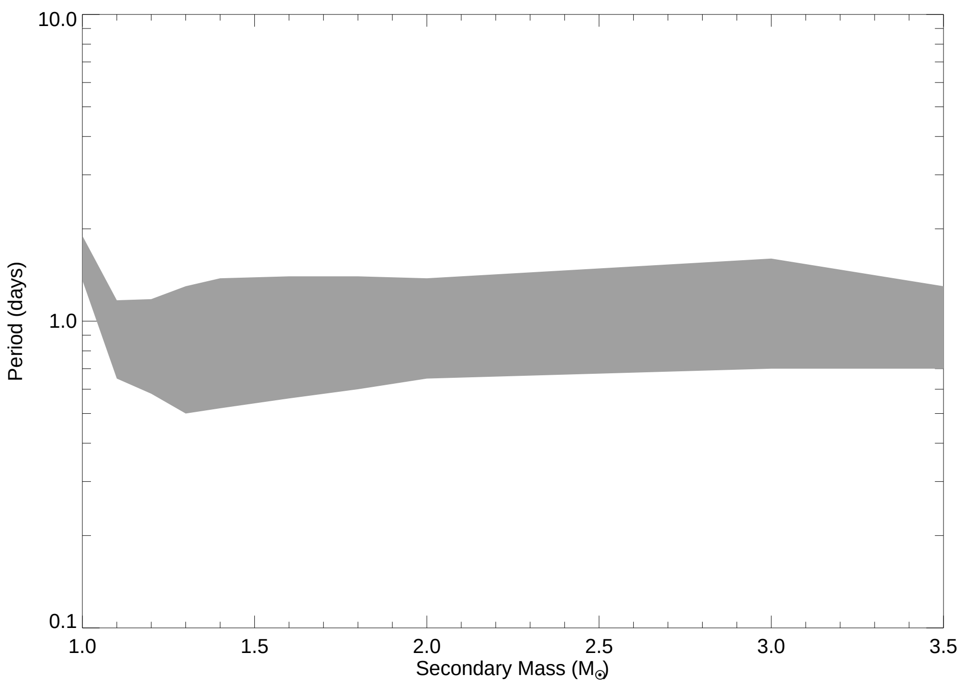

Fig. 1.— Parameter space of the initial orbital period and donor star mass for binary systems which are able to evolve to UCXBs under the influence of a CB disk within 13.7 Gyr.

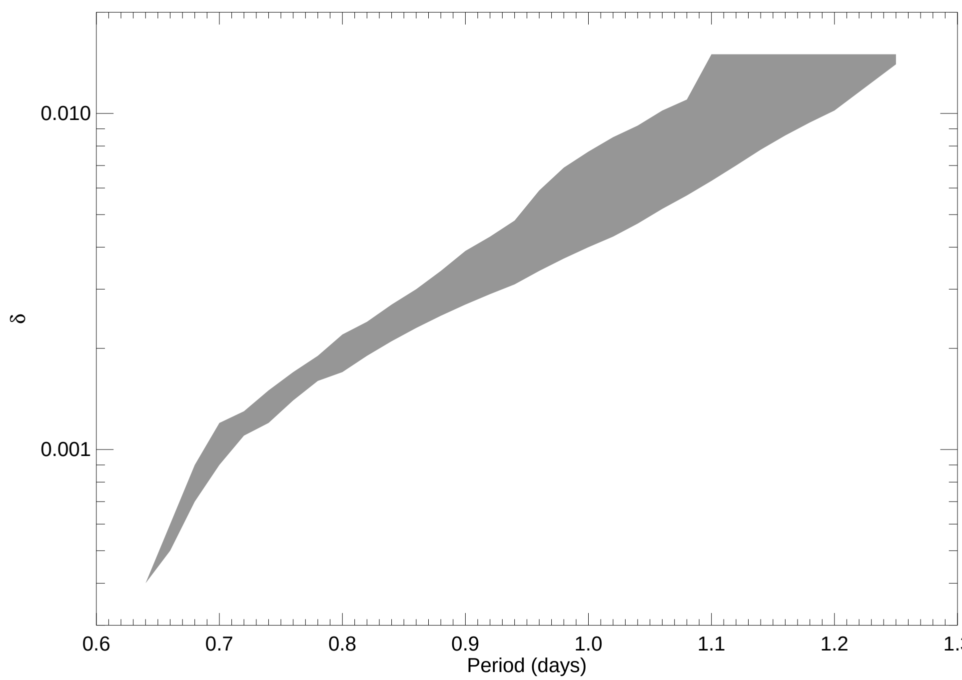

Fig. 2.— The distribution of suitable CB disk parameter δ and initial orbital period for progenitor binary systems with $M_{2,\rm i} = 1.1 M_{\odot}$.

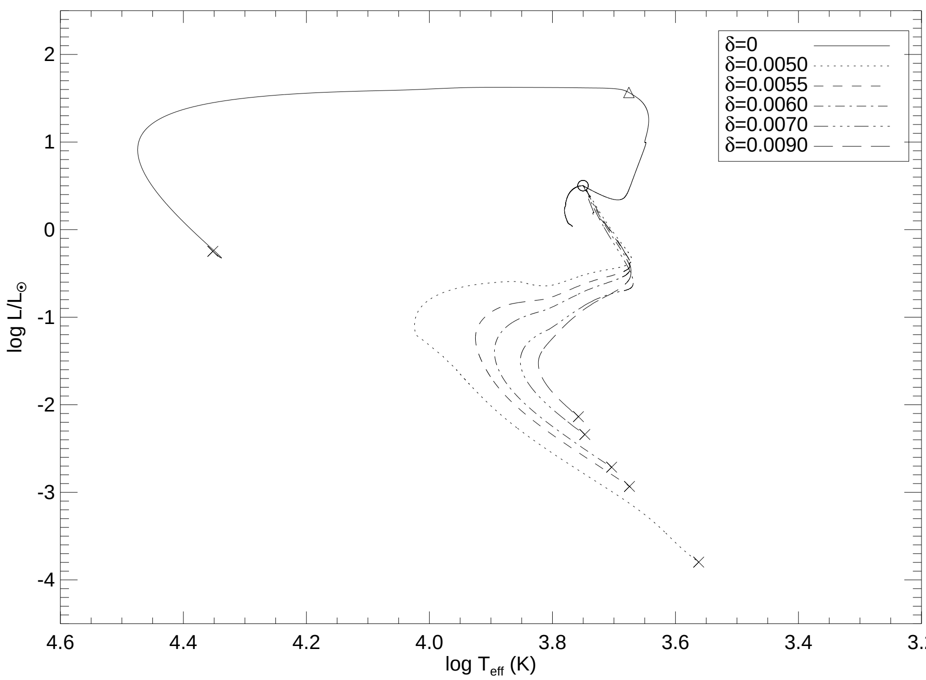

Fig. 3.— Evolutionary tracks of the donor star in a binary with $M_{2,\rm i} = 1.1 M_\odot$, $P_{\rm i} = 1.04$ day and different values of the CB disk parameter δ in the H-R diagram. The circles and triangles indicate the beginning and end of mass transfer, respectively. The crosses correspond to the end of the calculation.

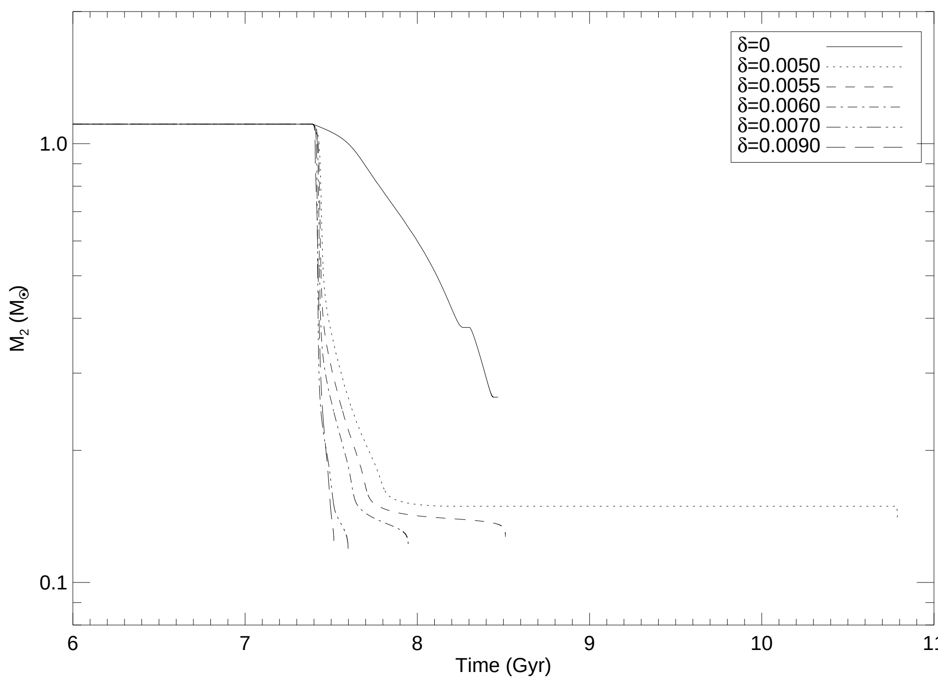

Fig. 4.— Evolution of the donor mass for a binary with $M_{2,\mathrm{i}} = 1.1 M_\odot$, $P_\mathrm{i} = 1.04$ day and different values of the CB disk parameter δ.

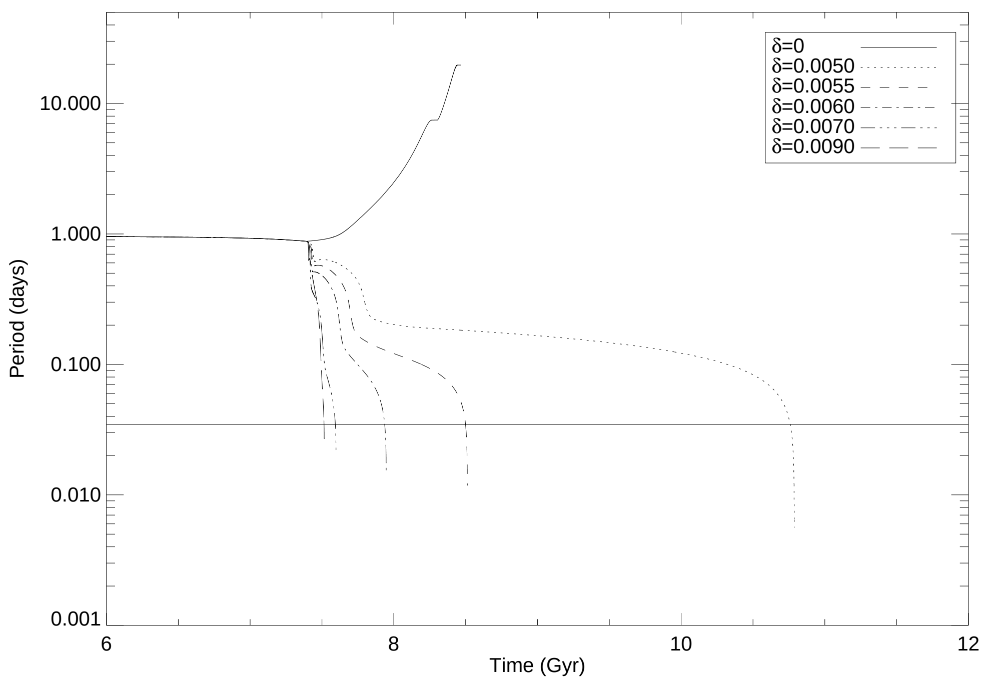

Fig. 5.— Evolution of the orbital period for a binary with $M_{2,\mathrm{i}} = 1.1 M_\odot$, $P_\mathrm{i} = 1.04$ day and different values of the CB disk parameter δ. The horizontal line corresponds to $P = 50$ mins.

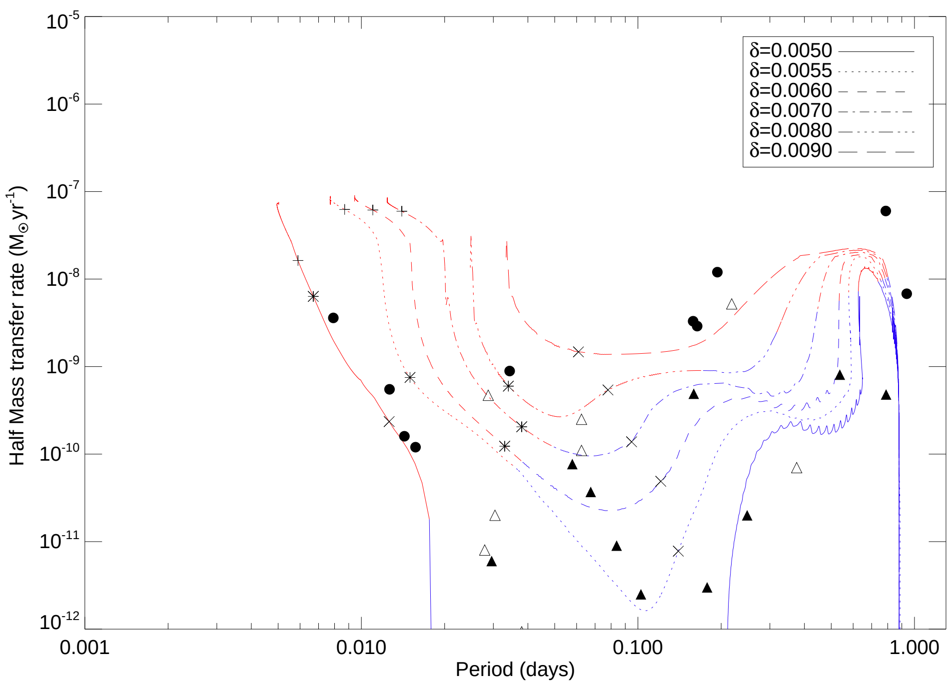

Fig. 6.— Evolution of mass accretion rate (or half of the mass transfer rate) vs. orbital period for binary systems with $M_2 = 1.1M_\odot$, $P_\mathrm{i} = 1.04$ day and different values of the CB disk parameter δ. The red and blue lines indicate persistent and transient accretion according to the criteria in Lasota et al. (2008) for a mixed-composition ($X = 0.1$, $Y = 0.9$) disk. Persistent (filled circles) and transient (triangles) LMXBs (including UCXBs) are also plotted for comparison. Here the open triangles mean that the derived mass accretion rates from observations are the upper limits. The symbols $\times, \ast, +$ on the evolutionary sequences denote where the composition of the donor in the binary is $X = 0.3$, 0.2, and 0.1 with $Y = 0.98 - X$ and $Z = 0.02$, respectively.

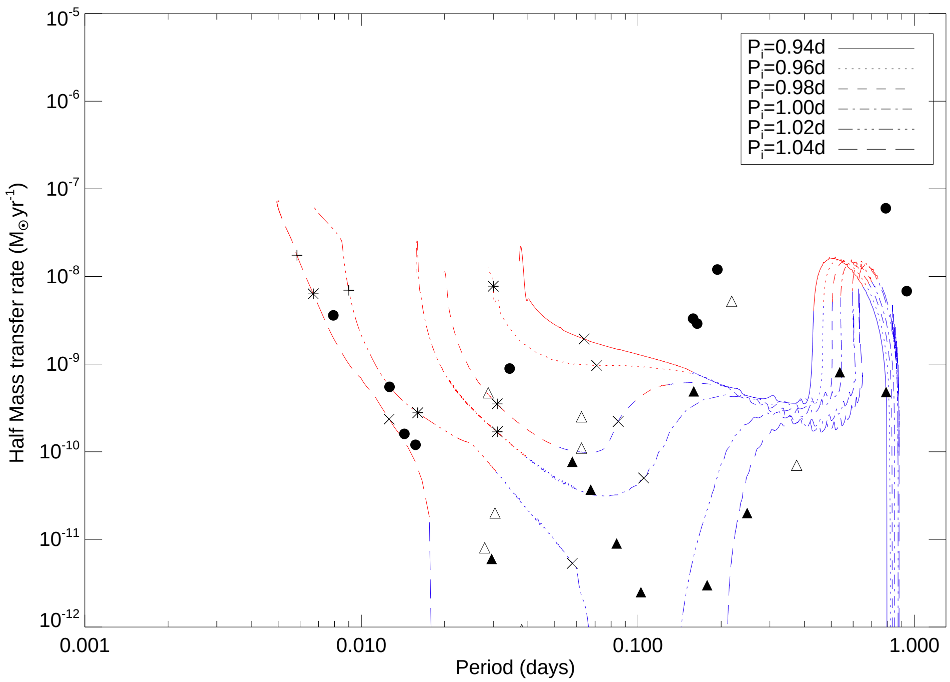

Fig. 7.— Same as in Fig. 6 but for binary systems with $M_{2,\mathrm{i}} = 1.1M_{\odot}$, $\delta = 5 \times 10^{-3}$, and $P_{\mathrm{i}} = 0.94 - 1.04$ day.

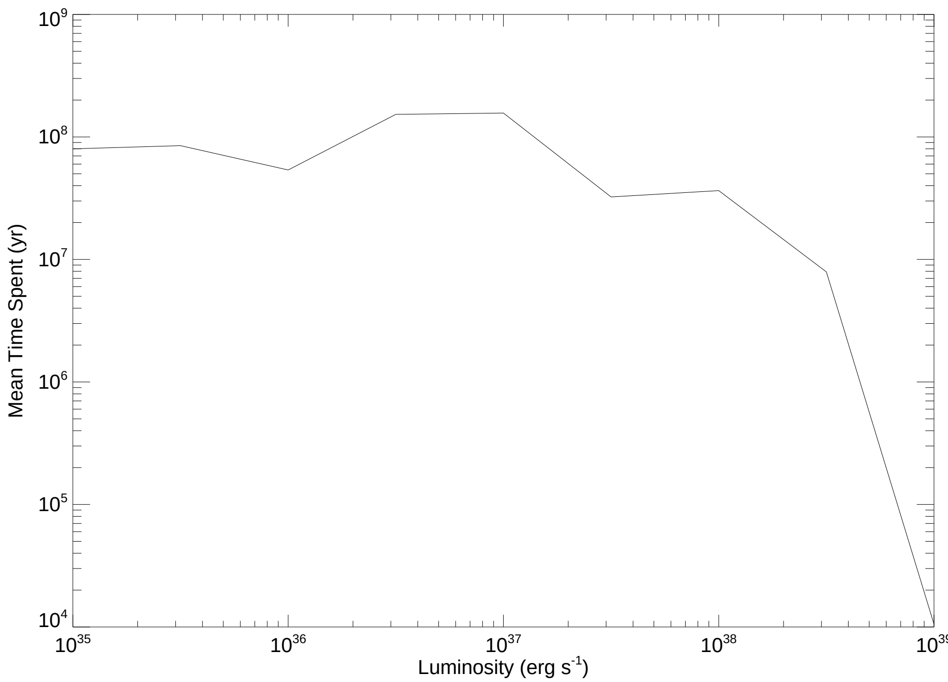

Fig. 8.— Mean X-ray lifetime spent by the LMXBs which could evolve to UCXBs within 13.6 Gyr at certain luminosities with $\delta = 0.005$. The mean life time decreases sharply when $L > 3 \times 10^{38}$ $\mathrm{ergs^{-1}}$.

Table 1: Parameters of known UCXBs

Systems	Type	$P_{\rm orb}$ (min)	$<\dot{M}>$ ($M_\odot$y^{-1})	Refs
4U 1820-30	P	11.4	$3.6^{+1.5}_{-0.6}\times10^{-9}$	1
4U 1543-624	P	18.2	$5.5^{+40}_{-4}\times10^{-10}$	2
4U 1850-087	P	20.6	$1.6\pm0.3\times10^{-10}$	3
M15 X-2	P	22.6	$1.2\pm0.2\times10^{-10}$	4
4U 1916-05	P	49.5	$8.9\pm1.3\times10^{-10}$	5
XTE J1807-294	T	40.07	$<8\pm7\times10^{-12}$	6,10
XTE J1751-305	T	42.42	$6\pm5\times10^{-12}$	6
XTE J0929-314	T	43.6	$<2\pm1.5\times10^{-11}$	6,11
4U 1626-67	T	41.4	$4.7^{+5.1}_{-3.2}\times10^{-10}$	7,8
SWIFT J1756.9-2508	T	54.7	$9.3\pm7\times10^{-13}$	9

Note. — Here the type means persistent (P) or transient (T) UCXBs. The mean mass transfer rates $<\dot{M}>$ listed here for persistent UCXBs are calculated by using the luminosities mentioned in the references and assuming accretion onto a $1.4M_\odot$ NS with 10 km radius. The uncertainties in the calculated $<\dot{M}>$ mainly come from the uncertainties of source distance, neutron star masses and radii, spectral fit goodness, and recurrence times of transient sources (see Heinke et al. (2007, 2009) for a thorough discussion for these factors).

References. — (1) Zdziarski et al. (2007), Kuulkers et al. (2003), Shaposhnikov & Titarchuk (2004); (2) Wang & Chakrabarty (2004), Schultz (2003); (3) Sidoli et al. (2006), Harris (1996), Paltrinieri et al. (2001); (4) Dieball et al. (2005), Hannikainen et al. (2005); (5) Juett & Chakrabarty (2006); (6) Heinke et al. (2009); (7) Chakrabarty (1998); (8) Krauss et al. (2007); (9) Lasota et al. (2008), Krimm et al. (2007); (10) Falanga et al. (2005); (11) Wijnands et al. (2005).

Table 2: The bifurcation periods $P_{\rm bif}$ and $P_{\rm rlof}$, and the shortest periods $P_{\rm min}$ achieved for a binary with $M_{2,\rm i} = 1.1 M_\odot$ and different values of δ.

δ	$P_{\rm bif}$ (day)	$P_{\rm rlof}$ (day)	$P_{\rm min}$ (min)
0	0.63	0.5	71
0.002	0.87	0.75	9
0.004	1.08	0.92	7
0.006	1.15	0.96	6
0.008	1.21	1.04	6
0.010	1.30	1.13	6